

Quasifission at extreme sub-barrier energies

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With the quantum diffusion approach the behavior of the capture cross-section is investigated in the reactions $^{92,94}\text{Mo} + ^{92,94}\text{Mo}$, $^{100}\text{Ru} + ^{100}\text{Ru}$, $^{104}\text{Pd} + ^{104}\text{Pd}$, and $^{78}\text{Kr} + ^{112}\text{Sn}$ at deep sub-barrier energies which are lower than the ground state energies of the compound nuclei. Because the capture cross section is the sum of the complete fusion and quasifission cross sections, and the complete fusion cross section is zero at these sub-barrier energies, one can study experimentally the unique quasifission process in these reactions after the capture.

The first evidences of hindrance for compound nucleus formation in the reactions with massive nuclei ($Z_1 \times Z_2 > 1600$) at energies near the Coulomb barrier were observed at GSI already long time ago [1–3]. The theoretical investigations showed that the probability of complete fusion depends on the competition between the complete fusion and quasifission after the capture stage [4–6]. As known, this competition can strongly reduce the value of the fusion cross section and, respectively, the value of the evaporation residue cross section in reactions producing heavy and superheavy nuclei. The quasifission is related to the binary decay of the nuclear system after the capture, but before a compound nucleus is formed which could exist at angular momenta treated [4–7]. The quasifission process was originally ascribed only to reactions with massive nuclei. But it is the general phenomenon which takes place in reactions with the massive and medium-mass nuclei at energies above and below the Coulomb barrier [8, 9]. The mass and angular distributions of the quasifission products depend on the entrance channel and the bombarding energy [7].

For systems with negative Q -value, the complete fusion cross section σ_{fus} is equal to zero at bombarding energies $E_{c.m.} < E_{c.m.}^0 = -Q$:

$$\sigma_{fus}(E_{c.m.} < E_{c.m.}^0) = 0.$$

This expression implies that the fusion cross section or the fusion probability P_{fus} must go to zero when the center-of-mass energy $E_{c.m.}$ approaches the ground state energy, $-Q$, of the compound nucleus. Since the sum of the complete fusion cross section σ_{fus} and the quasifission cross section σ_{qf} gives the capture cross section

$$\sigma_{cap} = \sigma_{fus} + \sigma_{qf},$$

at $E_{c.m.} < E_{c.m.}^0 = -Q$ we have

$$\sigma_{cap}(E_{c.m.} < E_{c.m.}^0) = \sigma_{qf}.$$

So, at these deep sub-barrier energies the quasifission is only contribution to the capture cross section and there is no the overlapping between the fusion-fission and quasifission processes as at higher bombarding energies. At

deep sub-barrier energies, the quasifission event corresponds to the formation of a nuclear-molecular state or dinuclear system with small excitation energy that separates by quantum tunneling through the Coulomb barrier in a binary event with mass and charge close to the entrance channel.

Although many measurements do not reach such deep sub-barrier energies $E_{c.m.} < E_{c.m.}^0 = -Q$, it is still possible to find systems with relatively small values of $V_b - E_{c.m.}^0 = V_b + Q$ ($V_b = V(R_b)$ is the height of the Coulomb barrier for the spherical nuclei, R_b is the position of this barrier) for the experimental study of the quasifission process. The purpose of the present article is to find such type of systems and to estimate the capture cross sections at $E_{c.m.} < E_{c.m.}^0 = -Q$. The quantum diffusion approach [8–11] is applied to study the capture process more thoroughly.

In our quantum diffusion approach [8–11] the collisions of nuclei are treated in terms of a single collective variable: the relative distance between the colliding nuclei. The nuclear deformations are taken into account through the dependence of the nucleus-nucleus potential on the quadrupole deformations and mutual orientations of the colliding nuclei. Our approach regards the fluctuation and dissipation effects in the collision of heavy ions and models the coupling with various channels (for example, coupling of the relative motion with low-lying collective modes such as dynamical quadrupole and octupole modes of the target and projectile [12]). We have to mention that many quantum-mechanical and non-Markovian effects accompanying the passage through the potential barrier are considered in our formalism [10, 13] through the friction and diffusion. To calculate the nucleus-nucleus interaction potential $V(R)$, we use the procedure presented in Refs. [8–10]. For the nuclear part of the nucleus-nucleus potential, the double-folding formalism with a Skyrme-type density-dependent effective nucleon-nucleon interaction is used. The absolute values of the quadrupole deformation parameters β_2 of deformed nuclei were taken from Ref. [17].

The calculated results for all reactions are obtained with the same set of parameters as in Refs. [9, 10] and are rather insensitive to a reasonable variation of them. One

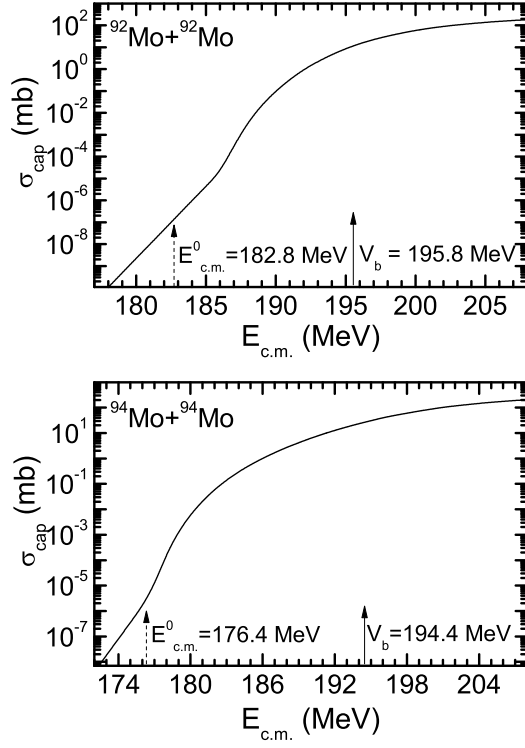


FIG. 1: The calculated capture cross sections vs $E_{\text{c.m.}}$ for the reactions $^{92,94}\text{Mo} + ^{92,94}\text{Mo}$. The dashed and solid arrows show $E_{\text{c.m.}} = E_{\text{c.m.}}^0 = -Q$ and $E_{\text{c.m.}} = V_b$, respectively.

should stress that diffusion models, which also include quantum statistical effects, were proposed in Refs. [14–16] too.

Symmetric and near symmetric dinuclear systems with neutron-deficient stable nuclei have the smallest values of $(V_b + Q)$. For example, the sub-barrier energies with respect to the Coulomb barrier are $V_b - E_{\text{c.m.}}^0 = V_b + Q = 13, 14.8, 18, 19.4, 21.8 \text{ MeV}$ for the systems $^{92}\text{Mo} + ^{92}\text{Mo}$, $^{104}\text{Pd} + ^{104}\text{Pd}$, $^{94}\text{Mo} + ^{94}\text{Mo}$, $^{100}\text{Ru} + ^{100}\text{Ru}$, $^{78}\text{Kr} + ^{112}\text{Sn}$, respectively. Here predictions of unknown mass-excesses of the compound nuclei are taken from Ref. [18]. In Figs. 1–3 the calculated capture cross sections for these reactions are presented. All systems show a steady decrease of the sub-barrier fusion cross sections with a pronounced change of slope. With $E_{\text{c.m.}}$ decreasing below the Coulomb barrier the interaction changes because at the external turning point the colliding nuclei do no more reach the region of the nuclear interaction where the friction plays a role. As result, at smaller $E_{\text{c.m.}}$ the cross sections fall with a smaller rate. For sub-barrier energies, the results of calculations are very sensitive to the quadrupole deformation parameters β_2 of the interacting nuclei. The influence of nuclear deformation is straightforward. If the target and projectile nuclei are prolate in their ground states, the Coulomb field on its tips is lower than on its sides. This increases the capture probability at energies below the barrier corresponding to the spherical nuclei. The enhancement of sub-barrier capture for the reactions $^{104}\text{Pd} + ^{104}\text{Pd}$, $^{100}\text{Ru} + ^{100}\text{Ru}$, and $^{78}\text{Kr} +$

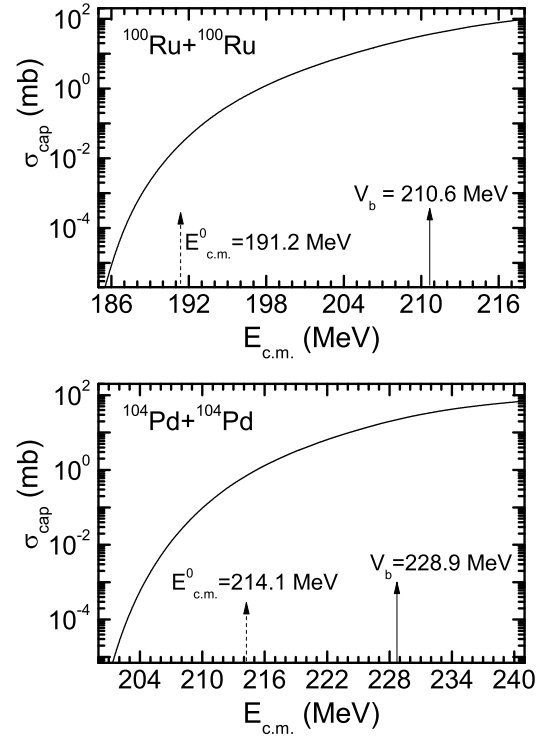


FIG. 2: The same as in Fig. 1, but for the reactions $^{100}\text{Ru} + ^{100}\text{Ru}$ and $^{104}\text{Pd} + ^{104}\text{Pd}$.

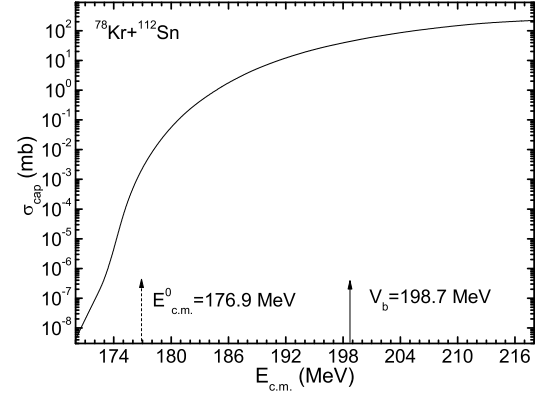


FIG. 3: The same as in Fig. 1, but for the $^{78}\text{Kr} + ^{112}\text{Sn}$ reaction.

^{112}Sn in the contrast to the reactions $^{92,94}\text{Mo} + ^{92,94}\text{Mo}$ is explained by the deformation effect: the deformations in the former systems are larger the ones in the later systems.

In Figs. 1–3 the calculated capture cross sections at $E_{\text{c.m.}} = E_{\text{c.m.}}^0 = -Q$ are $\sigma_{\text{cap}} = 0.2 \text{ nb}$, 5.1 nb , $2.3 \mu\text{b}$, $24.4 \mu\text{b}$, and 0.7 mb for the reactions $^{92}\text{Mo} + ^{92}\text{Mo}$, $^{94}\text{Mo} + ^{94}\text{Mo}$, $^{78}\text{Kr} + ^{112}\text{Sn}$, $^{100}\text{Ru} + ^{100}\text{Ru}$, and $^{104}\text{Pd} + ^{104}\text{Pd}$, respectively. So, $^{104}\text{Pd} + ^{104}\text{Pd}$, $^{100}\text{Ru} + ^{100}\text{Ru}$, and $^{78}\text{Kr} + ^{112}\text{Sn}$ are the optimal reactions for studying capture and quasifission at deep sub-barrier energies $E_{\text{c.m.}} < E_{\text{c.m.}}^0 = -Q$ where the complete fusion channel is closed ($\sigma_{\text{fus}} = 0$). At these sub-barrier energies the

quasifission process can be studied in future experiments: from the measurement of the mass (charge) distribution in collisions with total momentum transfer one can show the distinct components which are due to quasifission (with respect to the quasielastic components). Because the angular momentum is $J < 10$ at these energies, the angular distribution would have a small anisotropy. The low-energy experimental quasifission data would probably provide straight information since the high-energy data may be shaded by competing the fusion-fission processes. The lifetime of nuclear molecule formed seems to be long enough to separate it mass from other reaction products. Then one can observe the decay of this molecule into two fragments.

In conclusion, the quantum diffusion approach was ap-

plied to calculate the capture cross sections for the reactions $^{92}\text{Mo} + ^{92}\text{Mo}$, $^{104}\text{Pd} + ^{104}\text{Pd}$, $^{94}\text{Mo} + ^{94}\text{Mo}$, $^{100}\text{Ru} + ^{100}\text{Ru}$, and $^{78}\text{Kr} + ^{112}\text{Sn}$ at extreme sub-barrier energies which are too low for complete fusion. The quasifission near the entrance channel is the unique binary decay process after the capture. The reactions $^{104}\text{Pd} + ^{104}\text{Pd}$, $^{100}\text{Ru} + ^{100}\text{Ru}$, and $^{78}\text{Kr} + ^{112}\text{Sn}$ seem to be optimal systems for a experimental study of the true quasifission at extreme sub-barrier energies.

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